Measurement of the *CP*-violating phase ϕ_s in $B_s^0 \to J/\psi\phi$ decays in ATLAS at 13 TeV

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ATLAS EXPERIMENT

THE UNIVERSITY OF NEW MEXICO

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This is a study by the ATLAS Experiment at the LHC, of parameters associated with *CP*-violation in *B* mesons.

CP-violation in the Standard Model

- The CKM matrix is a 3×3 complex, unitary matrix whose elements represent the strength of flavor-changing weak interactions.

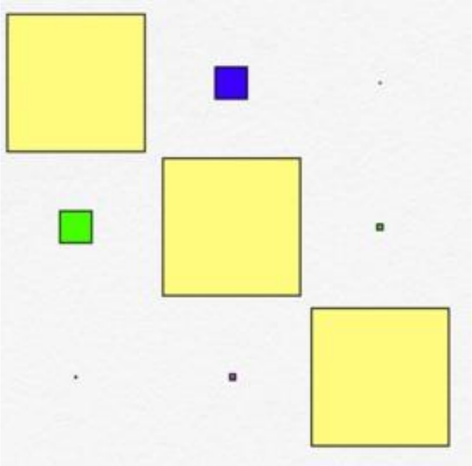
$$\begin{bmatrix} d' \\ s' \\ b' \end{bmatrix} = V_{CKM} \begin{bmatrix} d \\ s \\ b \end{bmatrix}, \text{ where } V_{CKM} = \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix}$$

An $N \times N$ matrix will have $N(N-1)/2$ real parameters (Euler Angles) and $(N-1)(N-2)/2$ nontrivial phase angles.

V_{CKM} ➡ 3 real parameters and 1 complex phase – origin of *CP*-violation in SM

- Using Wolfenstein's parametrization[1],

$$\begin{pmatrix} 1 - \lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1 - \lambda^2/2 & A\lambda^2 \\ A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4) \Rightarrow$$



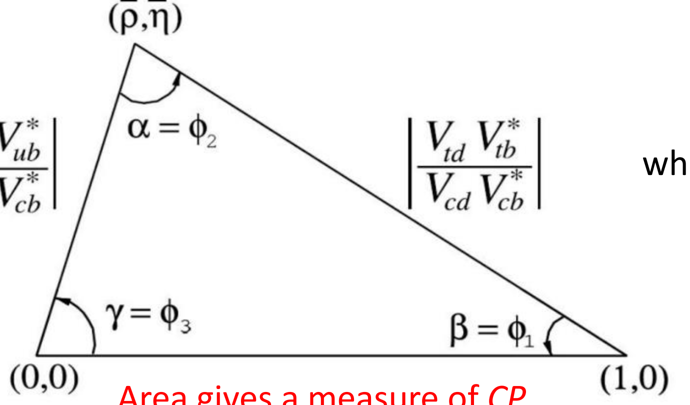
Relative quark coupling strengths

1. A. Ceccucci, Z. Ligeti and Y. Sakai, 'CKM Quark-Mixing Matrix', Particle Data Group, Revised March 2020

Exploiting the unitarity of the CKM matrix, we get 9 conditions from which 3 triangles could be created.

$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$

most commonly used, obtained by multiplying 1st and 3rd column of CKM matrix



where

$$\alpha = \arg\left(-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right);$$

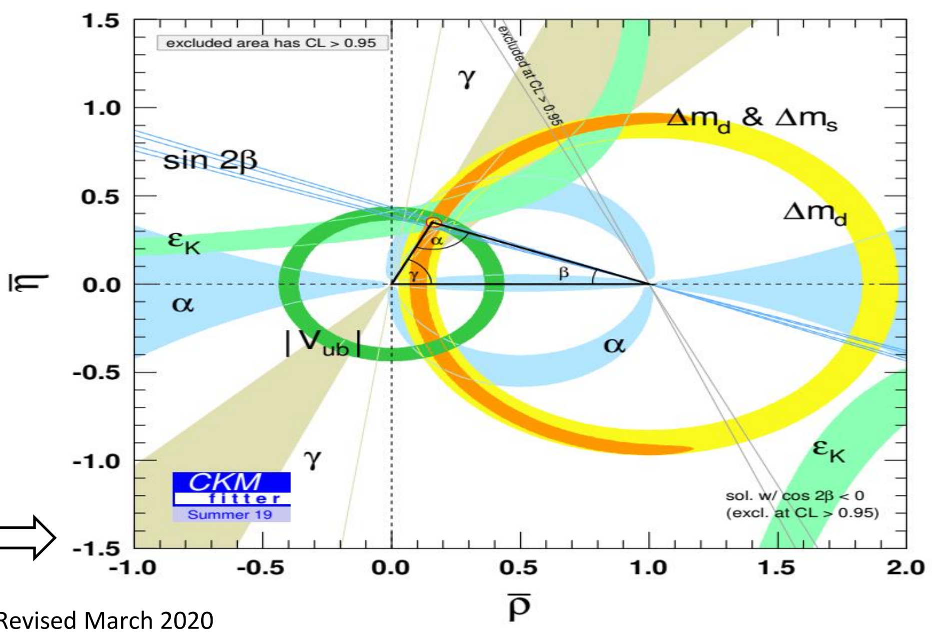
$$\beta = \arg\left(-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right); \text{ and}$$

$$\gamma = \arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right).$$

Area gives a measure of *CP* violation in the Standard Model.

The aim of experimental study of *CP* violation is to measure the angles α, β and γ precisely for each unitarity triangle by studying the decays involving quark transitions corresponding to the matrix elements V_{ij}. If the Standard Model is the correct description of our universe, then the unitarity of CKM matrix should hold.

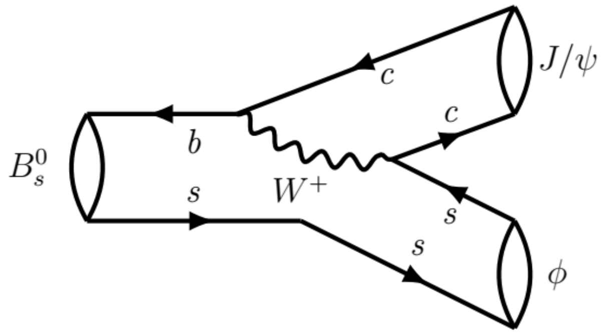
Unitarity triangle formed by the constraints from various measurements[1].



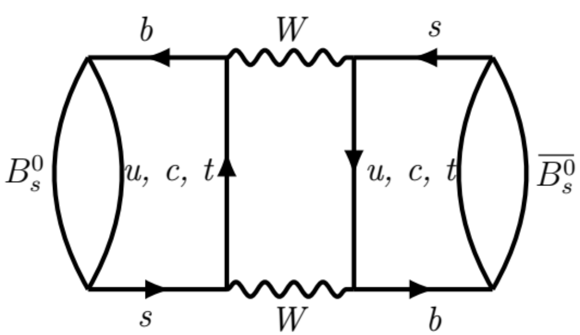
1. A. Ceccucci, Z. Ligeti and Y. Sakai, 'CKM Quark-Mixing Matrix', Particle Data Group, Revised March 2020

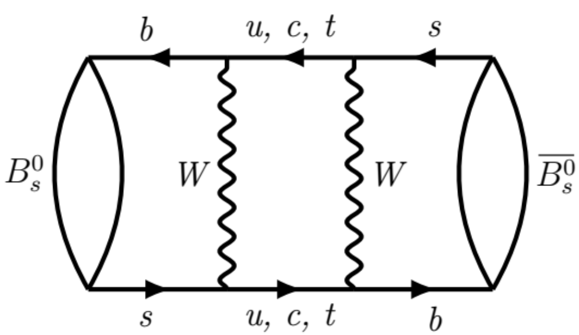
$B_s^0 \to J/\psi\phi$ Decay and $B_s^0 - \overline{B_s^0}$ Mixing

- Decays of *B* mesons are of great interest due to their heavy mass which provides several decay paths, most of them yet to be explored.
- Two competing processes in our study – a direct decay of B_s^0 and a decay from $B_s^0 - \overline{B_s^0}$ mixing to same final state in which an interference can be observed.
- $B_s^0 \to J/\psi\phi$ decay proceeds via the $\bar{b} \to \bar{c}cs$ transition as shown by the tree-level diagram.



- B_s^0 can transform to its antiparticle $\overline{B_s^0}$ in a phenomenon called mixing or oscillation.





SM parameters in $B_s^0 \to J/\psi\phi$ decay

ϕ_s

- A weak phase difference between mixing amplitude and decay amplitude
- Related to the CKM matrix via $\phi_s \approx -2\beta_s$, with $\beta_s = \arg[-V_{ts}V_{tb}^*/V_{cs}V_{cb}^*]$.
- Assuming no New Physics is involved, a value of $-2\beta_s = 0.03396 \pm 0.00011$ was predicted by the CKMFitter group[1] and $-2\beta_s = 0.03700 \pm 0.00104$ by the UTfit Collaboration[2].
- Highly sensitive to New Physics.

Γ_s

- The average of the decay widths of light and heavy mass eigenstates.
- Not sensitive to New Physics.

$\Delta\Gamma_s$

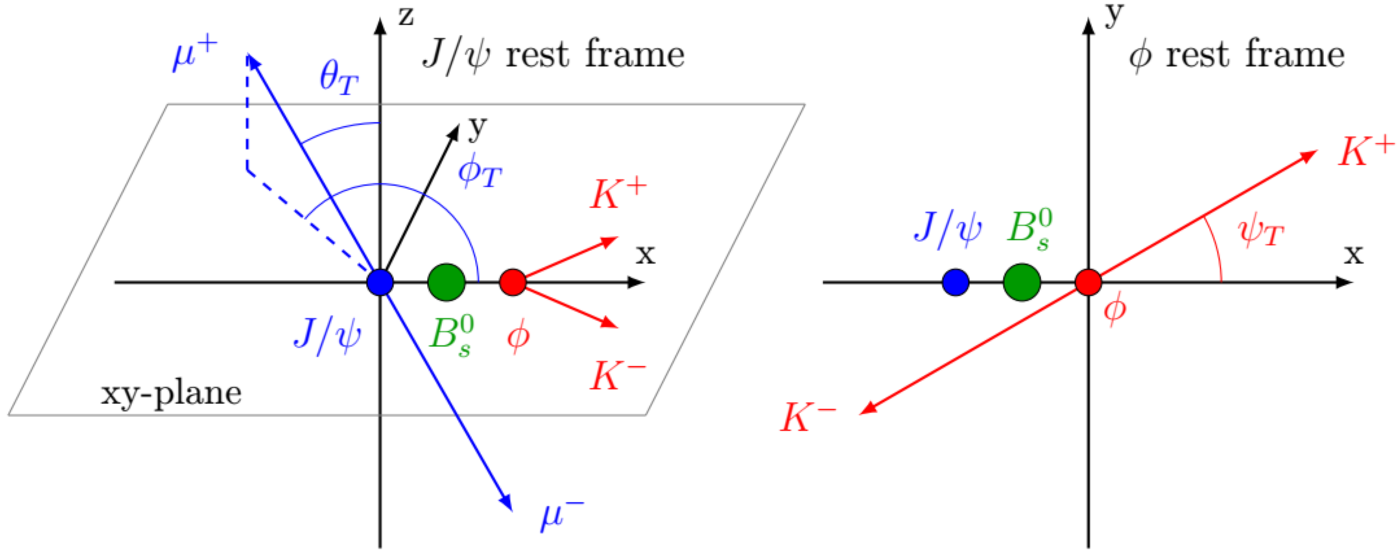
- Difference between the decay widths of light and heavy mass eigenstates.
- In the Standard Model, the value[3] for $\Delta\Gamma_s$ is predicted to be (0.085 ± 0.015) ps^{-1}.
- Not sensitive to New Physics but can be used to test the Standard Model.

If New Physics is involved, we expect different value of ϕ_s compared to Standard Model prediction.

1. CKMfitter group, Charles, J. *et al.*, *Current status of the Standard Model CKM fit and constraints on* ΔF *= 2 New Physics*, Phys. Rev. D **91** (2015) 073007, Numbers updated using the results from the 2019 values in https://ckmfitter.in2p3.fr/www/results/plots_summer19/ckm_res_ summer19.html, arXiv: 1501.05013 [hep-ph].
2. UTfit Collaboration, M. Bona *et al.*, *The unitarity triangle fit in the standard model and hadronic parameters from lattice QCD: A reappraisal after the measurements of* Δm_s *and* $BR(B \to \tau\vartheta_\tau)$, JHEP **10** (2006) 081, Numbers updated to the 2018 results from https://www.utfit.org/UTfit/ResultsSummer2018SM, arXiv: hep-ph/0606167 [hep-ph].
3. M. Artuso, G. Borissov and A. Lenz, CP violation in the B_s^0 system, Rev. Mod. Phys. 88 (2016) 045002, [Addendum: Rev. Mod. Phys. 91, no. 4, 049901 (2019)], arXiv: 1511.09466 [hep-ph].

Angular Analysis for Decomposition to *CP* Eigenstates

Final state of a $B_s^0 \to J/\psi\phi$ decay is an admixture of *CP* even and odd states. So, a time dependent angular analysis where the statistical contribution of *CP* even and odd states, are required for the extraction of SM parameters.



- In the transversity angle $\Omega(\theta_T, \psi_T, \phi_T)$ basis, four time dependent decay amplitudes - A_0 and $A_\parallel$ corresponding to *CP* –even eigenstates and $A_\perp$ and A_S corresponding to *CP*-odd eigenstates can be defined and their values at $t = 0$ are observables in this study.

- In addition, four relative strong phases $\delta_0, \delta_{||}$, $\delta_\perp$ and δ_S are also defined as observables with $\delta_0 = 0$ by convention.

The event is mainly identified by the final decay products:

$$B_s^0 \to J/\psi\phi \text{ where } J/\psi \to \mu^+\mu^- \text{ and } \phi \to K^+K^-$$

Step 1: Flavor Tagging - Identify the flavor of B^0 meson produced.
The flavor of the initial B^0 meson is identified through opposite side tagging (OST) where the information of the $\overline{B^0}$ produced is used.

Step 2: Trigger Selection - Select the events of interest from the large pool of $\mu^+\mu^-$ and K^+K^- events.
Events should pass certain conditions called triggers. A few important triggers for the reconstruction of $B_s^0 \to J/\psi\phi$ are

- Setting transverse momentum (p_T) thresholds for charged pairs of muons and kaons.
- Constraining invariant mass for charged pairs of muons and kaons.
- Each event should form at least one reconstructed primary vertex from at least four Inner Detector tracks.
- At least one pair of charged muons reconstructed using information from both Inner Detector and Muon Spectrometer.

Step 3: Candidate Selection - Fit the selected $\mu^+\mu^-$ and K^+K^- to a common vertex.
Candidate events for $B_s^0 \to J/\psi(\mu^+\mu^-)\phi(K^+K^-)$ are selected by fitting the tracks of each combination of $J/\psi \to \mu^+\mu^-$ and $\phi \to K^+K^-$ decays to a common vertex. In our study, a total of 2 977 526 B_s^0 candidates are collected within the mass range of 5.150-5.650 GeV.

Step 4: Proper decay time calculation for each candidate.

$$t = \frac{L_{xy} m_B}{p_{T_B}}$$

- L_{xy} is the transverse decay length.
- m_B is the mass of the B_s^0 meson.
- p_{T_B} is the reconstructed transverse momentum.

An unbinned maximum likelihood fit is performed to extract physics parameters of the $B_s^0 \rightarrow J/\psi\phi$ decay.

$$\ln L = \sum_i^N w_i \ln[f_s . F_s(m_i, t_i, \sigma_{mi}, \sigma_{ti}, \Omega_i, P_i(B|Q_x), p_{\mathrm{T}_i}) + f_s . f_{B^0} . F_{B^0}(m_i, t_i, \sigma_{mi}, \sigma_{ti}, \Omega_i, P_i(B|Q_x), p_{\mathrm{T}_i})$$
$$+ f_s . f_{\Lambda_b} . F_{\Lambda_b}(m_i, t_i, \sigma_{mi}, \sigma_{ti}, \Omega_i, P_i(B|Q_x), p_{\mathrm{T}_i}) + (1 - f_s . (1 + f_{B^0} + f_{\Lambda_b})) . F_{bkg}(m_i, t_i, \sigma_{mi}, \sigma_{ti}, \Omega_i, P_i(B|Q_x), p_{\mathrm{T}_i})]$$

Observables for each candidate

- Reconstructed mass *m.*
- Measured proper decay time *t.*
- Measured mass uncertainty σ_m.
- Measured proper decay time uncertainty σ_t.
- Tagging probability $P(B|Q_x)$ i.e., the probability of B meson in a particular flavor.
- Transversity angles $\Omega(\theta_T, \psi_T, \phi_T)$
- Transverse momentum p_{T_i}

Probability Density Functions (PDFs)

- F_s – signal
- F_{B^0} – B^0 background misidentified as B_s^0.
- F_{Λ_b} – Λ_b background misidentified as B_s^0.
- F_{bkg} – other backgrounds
- Obtained by extracting information for each candidate.

Fractions

- f_s – signal fraction.
- f_{B^0} – B^0 background fraction.
- f_{Λ_b} – Λ_b background fraction.
- Obtained from Monte Carlo simulations.

Results using 13 TeV Data

The following fit results are based on the 80 fb^{-1} of data collected in Run 2 (2015-2017) at center of mass energy 13 TeV.

Maximum likelihood fit result

Parameter	Value	Statistical uncertainty	Systematic uncertainty
ϕ_s [rad]	−0.081	0.041	0.022
$\Delta\Gamma_s$ [ps^{-1}]	0.0607	0.0047	0.0043
Γ_s [ps^{-1}]	0.6687	0.0015	0.0022
$\|A_\parallel(0)\|^2$	0.2213	0.0019	0.0023
$\|A_0(0)\|^2$	0.5131	0.0013	0.0038
$\|A_S(0)\|^2$	0.0321	0.0033	0.0046
$\delta_\perp - \delta_S$ [rad]	−0.25	0.05	0.04
Solution (a)			
$\delta_\perp$ [rad]	3.12	0.11	0.06
$\delta_\parallel$ [rad]	3.35	0.05	0.09
Solution (b)			
$\delta_\perp$ [rad]	2.91	0.11	0.06
$\delta_\parallel$ [rad]	2.94	0.05	0.09

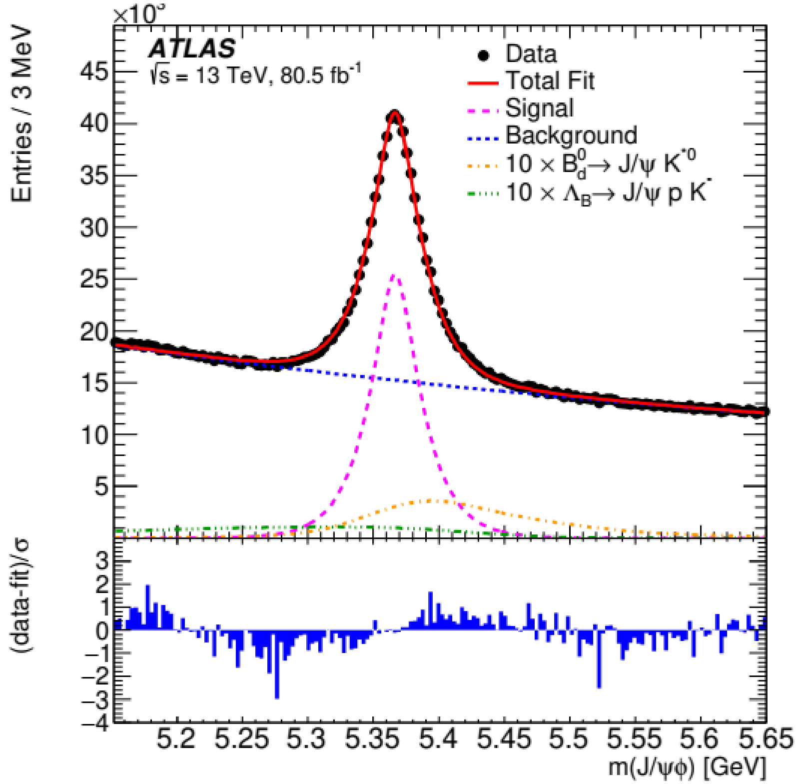
SM parameters

Additional parameters arising from angular analysis.

Some of the sources of systematic uncertainties in this fit include calibration in flavor tagging, Inner Detector misalignment, misidentified particles, best candidate selection, Monte Carlo simulations.

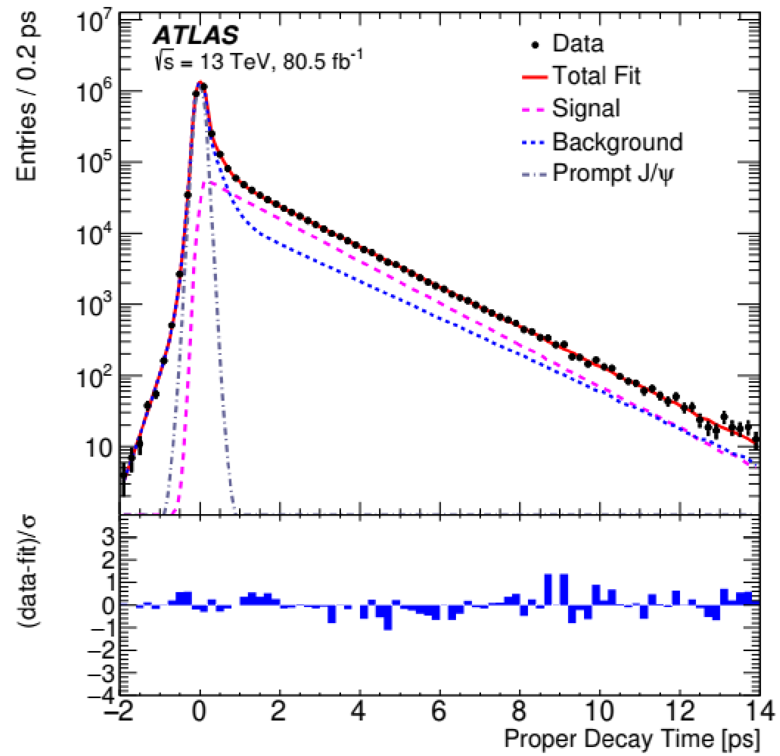
Results using 13 TeV data: Fit Projections[1]

mass of B_s^0 meson



The fitted mass agrees well with the world average value[2]

proper decay time of B_s^0 meson



Measured proper decay time is close to the world average value[3].

1. G. Aad *et al.* [ATLAS], [arXiv:2001.07115 [hep-ex]].
2. M. Tanabashi *et al*., *Review of Particle Physics*, Phys. Rev. D 98 (2018) 030001.
3. P.A. Zyla *et al*. (Particle Data Group), Prog. Theor. Exp. Phys. 2020, 083C01 (2020).

Combination with 7 and 8 TeV results

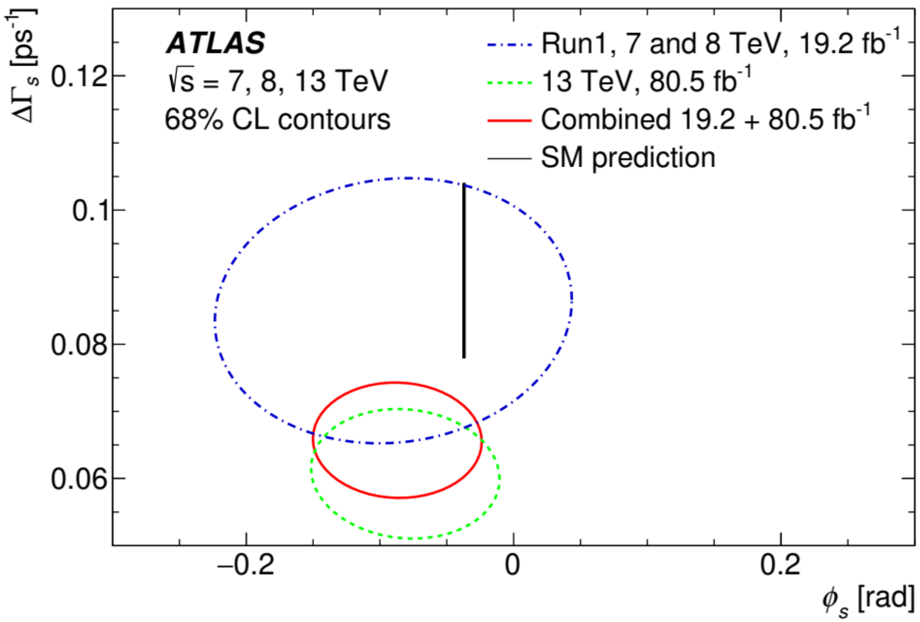
In order to bring down the uncertainties in *CP* violating parameters further, this result using 13 TeV data is statistically combined with the results using 7 and 8 TeV data in Run 1[1](2011-2012) leading to the following results. The solutions (a) and (b) are treated separately.

Parameter	Solution (a) Value	Solution (a) Statistical uncertainty	Solution (a) Systematic uncertainty	Solution (b) Value	Solution (b) Statistical uncertainty	Solution (b) Systematic uncertainty
ϕ_s [rad]	−0.087	0.036	0.021	−0.087	0.036	0.021
$\Delta\Gamma_s$ [ps^{-1}]	0.0657	0.0043	0.0037	0.0657	0.0043	0.0037
Γ_s [ps^{-1}]	0.6703	0.0014	0.0018	0.6704	0.0014	0.0018
$\lvert A_{\parallel}(0)\rvert^2$	0.2220	0.0017	0.0021	0.2218	0.0017	0.0021
$\lvert A_0(0)\rvert^2$	0.5152	0.0012	0.0034	0.5152	0.0012	0.0034
$\lvert A_S\rvert^2$	0.0343	0.0031	0.0045	0.0348	0.0031	0.0045
$\delta_\perp$ [rad]	3.22	0.10	0.05	3.03	0.10	0.05
$\delta_\parallel$ [rad]	3.36	0.05	0.09	2.95	0.05	0.09
$\delta_\perp - \delta_S$ [rad]	−0.24	0.05	0.04	−0.24	0.05	0.04

1. G. Aad *et al*. [ATLAS],[arXiv: 1601.03297 [hep-ex]].

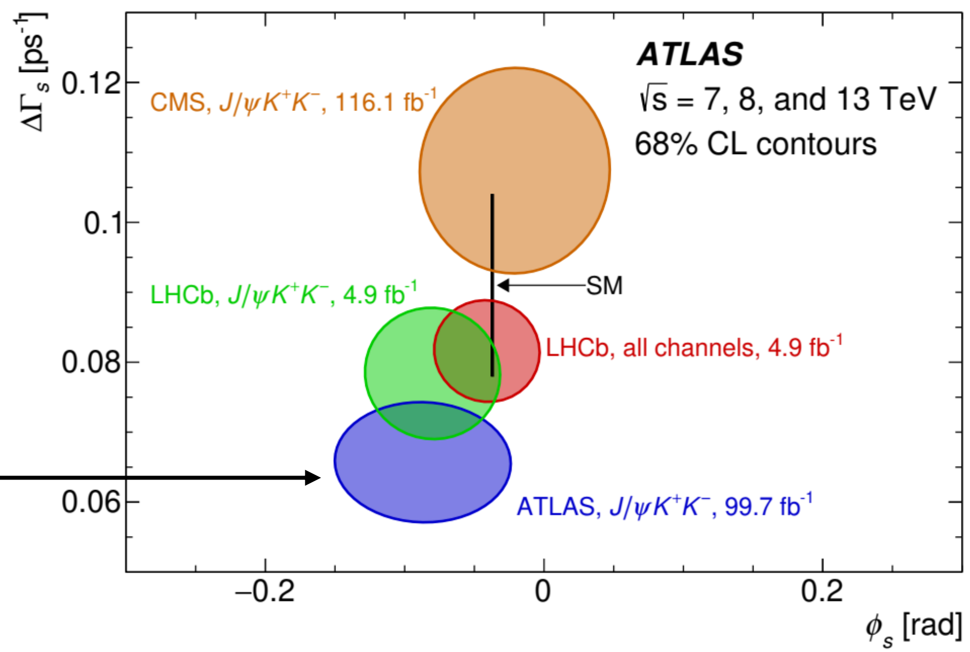
Contours[1] of 68% confidence level in the ϕ_s- $\Delta\Gamma_s$ plane

comparison of results using 7 and 8 TeV, 13 TeV and combined data.



comparison of results from ATLAS, CMS and LHCb experiments.

ATLAS Run 1 + Run 2



1. G. Aad *et al.* [ATLAS], [arXiv:2001.07115 [hep-ex]].

Conclusions

This study presents a measurement of the time-dependent *CP* asymmetry parameters in $B_s^0 \rightarrow J/\psi\phi$ decays from an 80 fb^{-1} data sample of proton-proton collisions collected with the ATLAS detector during the 13 TeV LHC run. The values from the 13 TeV analysis are consistent with those obtained in the previous ATLAS analysis using 7 TeV and 8 TeV data. The two measurements are statistically combined.

Parameter	Value	Statistical uncertainty	Systematic uncertainty
ϕ_s[rad]	-0.087	0.036	0.021
$\Delta\Gamma_s$[ps^{-1}]	0.0657	0.0043	0.0037
Γ_s [ps^{-1}]	0.6703	0.0014	0.0018

The measurement of the *CP*-violating phase ϕ_s is consistent with the Standard Model prediction, and it improves on the precision of previous ATLAS measurements[1].

1. G. Aad *et al*. [ATLAS],[arXiv: 1601.03297 [hep-ex]].

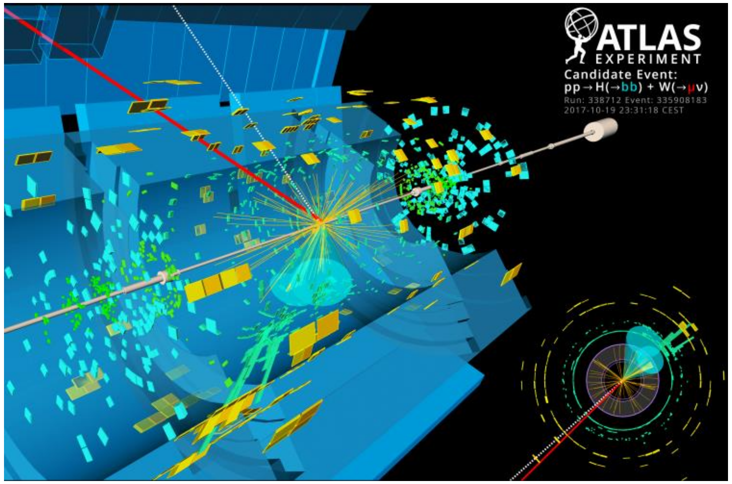
BACKUP SLIDES

What is the Large Hadron Collider?

Large Hadron Collider (LHC) – The world's largest and most powerful particle accelerator, situated 100m underground at CERN near Geneva, Switzerland. It lies in a tunnel of 27km circumference. It houses four main detectors – ATLAS, CMS, LHCb and ALICE.

What is going on at LHC?

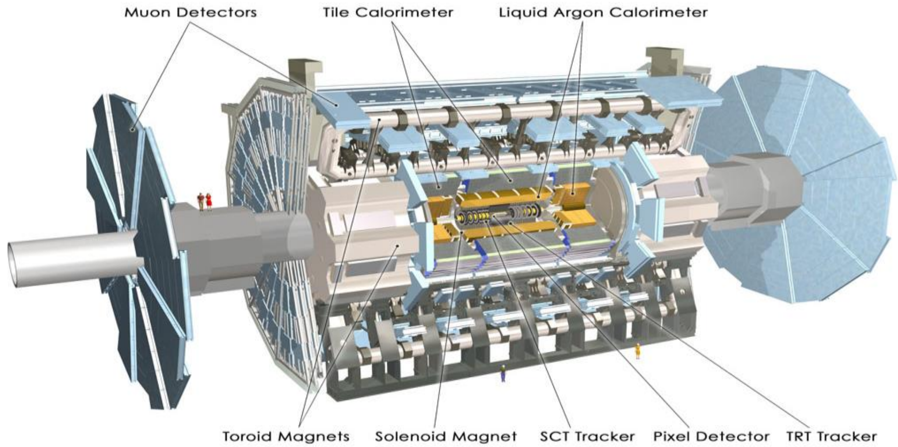
At LHC, two proton beams travel in opposite directions at close to the speed of light before they are made to collide. The collisions allow us to study fundamental particles and their interactions and to answer fundamental open questions pertaining to the origin of the universe by recreating the conditions similar to those shortly after the Big Bang.



A Higgs event where Higgs Boson decays to bottom and antibottom quarks at ATLAS detector

The UNM Collider Physics Group is involved in the ATLAS experiment.

ATLAS detector



The ATLAS detector is a multipurpose detector having dimensions of a cylinder 46m long and 25m in diameter. It is designed to detect the broadest possible signals that a New Physics process might provide.

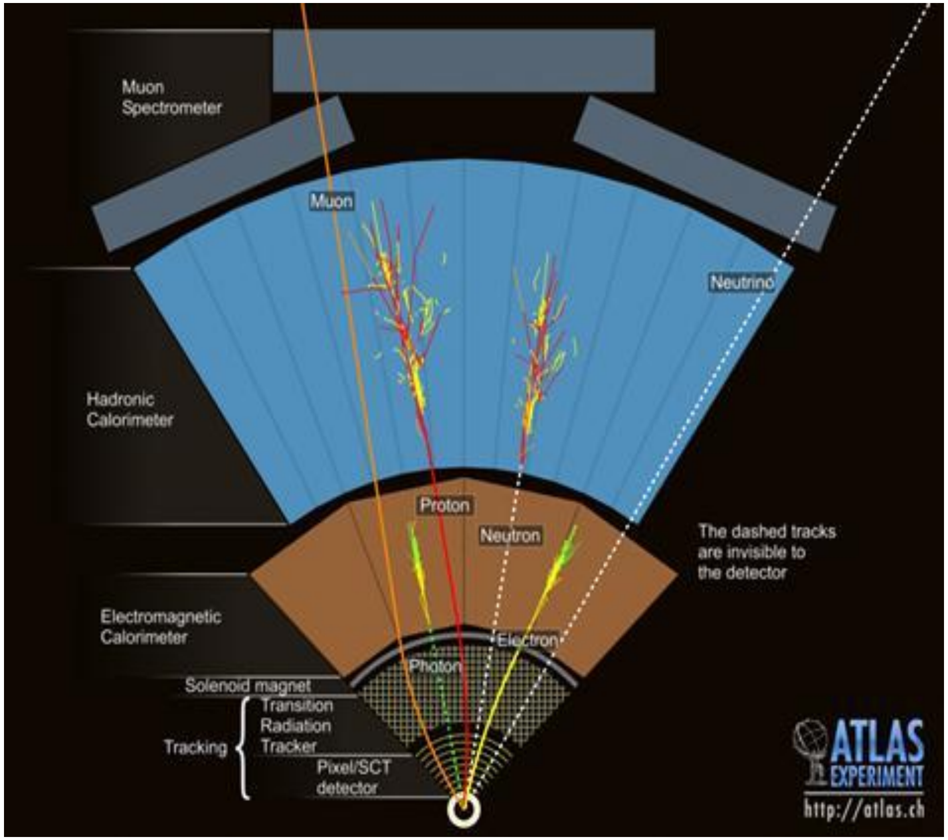
The ATLAS detector consists of subdetectors classified into three main components.

- Inner detector (ID) tracking system immersed in a 2T axial magnetic field.
- Electromagnetic and hadronic calorimeters.
- Muon spectrometer (MS).

The inner detector consists of

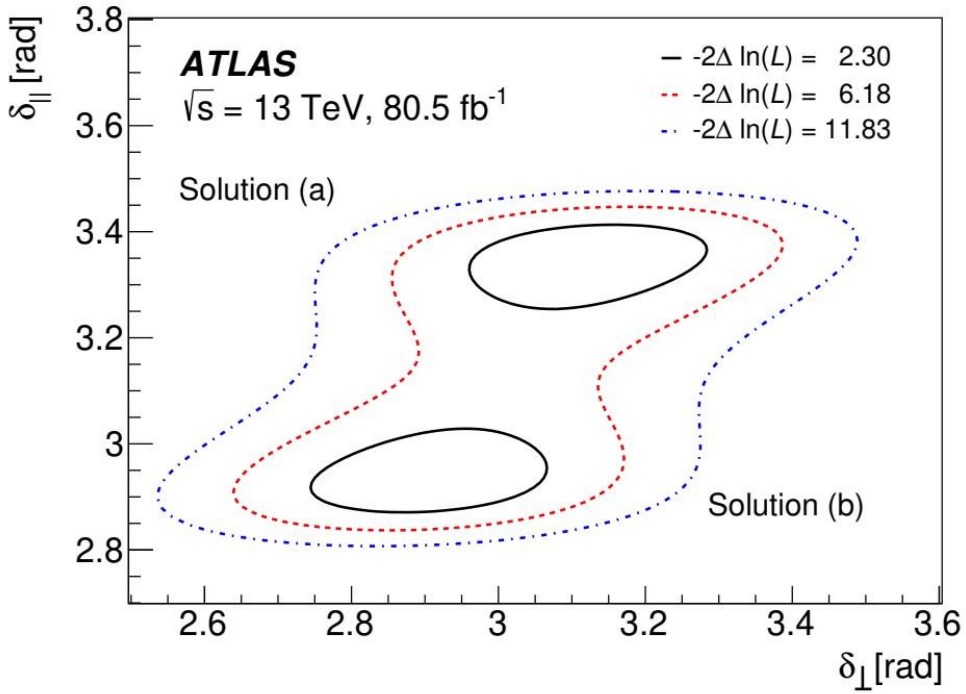
- Silicon pixel detector,
- Silicon microstrip detector, and
- Transition radiation tracking detectors.

computer generated cross sectional view of the ATLAS detector



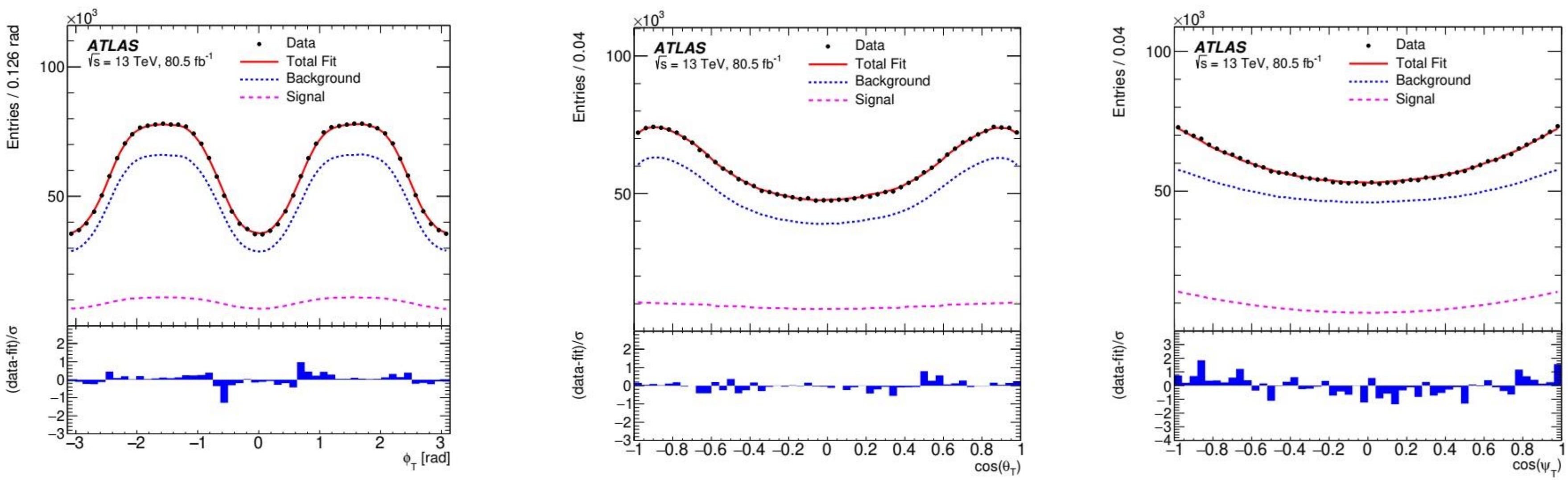
Two Solutions for Strong Phases - $\delta_{||}$ and $\delta_{\perp}$

Two solutions[1] (a) and (b) exist for the strong phases $\delta_{||}$ and $\delta_{\perp}$ due to the symmetry of the signal PDF while for other parameters, a single solution exists.



1. G. Aad *et al.* [ATLAS], [arXiv:2001.07115 [hep-ex]]

Fit projections for transversity angles $\Omega(\theta_T, \psi_T, \phi_T)$



1. G. Aad *et al.* [ATLAS], [arXiv:2001.07115 [hep-ex]]

Outline

- *CP*-violation in the Standard Model
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